

Article

The Coupling Coordination Degree and Constraints of the Water–Energy–Food Security System: A Case Study in Northeast China

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Abstract

Against the backdrop of significant climate change, resource constraints, and industrial upgrading, optimizing the coupling and coordination of the Water–Energy–Food (WEF) system in Northeast China is crucial for ensuring regional security and sustainable development. Existing research lacks long-term continuous analysis and inter-provincial comparisons. This article utilizes data from 2005 to 2023 to evaluate the development of the three provinces of Northeast China using a framework of 24 indicators covering safety, coordination, and resilience. Methodologies employed include the entropy weight method, the coupling coordination model, and the constraint model. The results show that: (1) The overall development level fluctuates with an overall upward trend, reaching a medium-coordinated level, and there are notable differences between provinces. (2) The coordination levels among provinces initially diverged but later converged, evolving from near dysfunction to a state of moderate coordination. Additionally, a bidirectional reinforcement mechanism has formed between system security and coupling coordination. (3) The key obstacles are deep-rooted in the system's structure and have cross-provincial implications due to interconnected infrastructure, among which energy self-sufficiency and water-use efficiency are the primary constraints. (4) Resilience serves as a key mediating variable in regulating the relationship between security and coordination within the WEF system. In order to achieve a high level of coordination between WEF systems, it is necessary to formulate tailor-made subsystem governance policies, enhance the technological empowerment of water and energy conservation and efficiency improvement, and promote the development of resilient infrastructure. This integrated approach could systematically resolve resource competition conflicts, thus enhancing the overall resilience and sustainability of regional development.

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1. Introduction

Water, energy, and food are the cornerstones of human well-being and sustainable socioeconomic development [1]. Rapid population growth and rising living standards continue to drive up demand for these resources. The United Nations projects that the

global population will reach 10 billion by 2050 [2], with food and energy demands expected to increase by 60% and 80%, respectively, compared to 2016 levels [3]. In stark contrast, global water demand is projected to increase by 20–30%, while approximately 4 billion people already live in severely water-scarce basins [4]. Faced with the multiple pressures of population growth, climate change, and resource scarcity, the complex interdependencies among water, energy, and food systems have become a central issue in sustainability science. Research on Water–Energy–Food (WEF) systems emphasizes understanding synergies and trade-offs through an analysis of their interlinkages, which provides a holistic framework for coordinating resource management and ensuring security [5].

As a vital industrial base, grain production hub, and ecological barrier for China, Northeast China shoulders the dual mission of regional revitalization and safeguarding national security [6]. Consequently, the security and synergy of its WEF systems are of paramount strategic importance. However, the region faces multiple pressures from climate change, resource constraints, and industrial transformation, leading to complex interactions within its WEF systems. This study focuses on the three northeastern provinces of China, utilizing 2005–2023 long-term panel data to construct a comprehensive evaluation framework encompassing three dimensions: safety, coordination, and resilience. By integrating entropy weight analysis, coupling coordination degree models, and constraint models, it systematically investigates the spatiotemporal evolution characteristics and constraints of the WEF system's coupling coordination degree. This study aims to reveal the spatiotemporal evolution and regional disparities in the coupling coordination of the WEF system in Northeast China and to identify the key constraints hindering its enhancement. The findings provide empirical and theoretical support for resource-based regions to improve resilience and coordination under multiple pressures.

2. Literature Review

2.1. Theoretical Framework

The Water–Energy–Food (WEF) nexus constitutes a fundamental, interdependent system critical to human survival and development. The relationships within this nexus are not merely correlative but form a complex network characterized by synergies, trade-offs, and feedback loops. In terms of synergies, water resources underpin both energy and food systems, enabling hydropower generation, agricultural irrigation, and thermal plant cooling. Energy, in turn, provides the critical impetus for water extraction, distribution, and food processing, thereby determining the security and stability of both water and food supplies. Food systems, as the primary consumers of water and energy, directly govern resource demand through their scale and structure. Reciprocally, they influence water and energy systems via bioenergy development, water-saving agriculture, and associated ecological feedbacks. In contrast to these synergies, the terms of trade-offs increased industrial and urban water use reduces agricultural water availability. The expansion of energy crops simultaneously causes a sharp decline in water and land resources for food production. Overuse of groundwater increases energy consumption and damages ecosystems. Furthermore, dynamic feedback mechanisms perpetuate these interactions, and regional climate change can alter precipitation patterns and the frequency of natural disasters while simultaneously impacting water supply, energy consumption, and food production. For instance, droughts exacerbate water scarcity while also affecting energy consumption and reducing grain yields. Interventions in grain, water resource, and energy management policies within the Northeast region can trigger a series of chain reactions across the area, further demonstrating the holistic and complex nature of the WEF system.

As a unified natural geographic unit, the Northeast region exhibits significant inter-provincial mobility within its WEF systems. The water resources of the Songliao River

Basin not only support agricultural irrigation in Heilongjiang and Jilin provinces but also ensure industrial and urban water supply for Liaoning. While energy systems like the Northeast Grid possess the infrastructure and technical capabilities for interprovincial power transmission, they simultaneously amplify risks during transmission, resulting in a highly interdependent system. The grain production of Heilongjiang and Jilin provinces not only meets local demand but also supplies the broader Chinese market. These interconnected flows of water, energy, and food create a tightly coupled regional system characterized by shared vulnerabilities. Addressing such a system, therefore, necessitates a regional perspective to manage resource redistribution, policy externalities, and systemic risks holistically.

2.2. Research Review and Novelty

Water, energy, and food form a mutually reinforcing system characterized by both relative opposition and absolute interconnection. Since the Bonn Conference in 2011 formally introduced the concept of the Water–Energy–Food (WEF) Nexus [7], it has garnered extensive attention from scholars worldwide. Research in this field has undergone a theoretical evolution, progressing from early single-resource management studies to examining pairwise relationships, and ultimately shifting toward integrated analysis of all three components [8,9]. This paper analyzes and summarizes existing research along two primary dimensions: evaluating coupling coordination relationships and identifying key influencing factors. Current methodologies increasingly combine quantitative research with qualitative analysis.

Firstly, in evaluating coupled coordination relationships, scholars primarily conduct analyses based on different theoretical frameworks and modeling approaches. From an evaluation perspective, early studies predominantly focused on unidimensional assessments of system “safety” or “stress-state-response” dynamics [10]. As research has deepened, metrics measuring the “synergy” or “coupling coordination degree” of subsystem interactions have emerged as core indicators [11,12]. In recent years, confronting escalating uncertainties and crises, the integration of “resilience” into comprehensive WEF system evaluation frameworks has gained prominence. This dimension assesses a system’s capacity for resistance, adaptation to change, and recovery to stability [13,14]. However, systematic empirical research in this area remains limited at the regional scale. Methodologically, quantitative approaches dominate the literature. For instance, Wang et al. employed a fuzzy set model to assess WEF system sustainability [10]; the coupling coordination degree model, valued for its ability to effectively characterize interaction levels among subsystems, has been widely applied by scholars in regional WEF system evaluations [11,12,15]. Furthermore, Data Envelopment Analysis (DEA) and its derivative models (such as the SBM model) have been extensively employed to measure the overall efficiency of WEF systems [16–18]. Additionally, methods like the Physical Input–Output Model [19], Life Cycle Assessment [20], Material Flow Analysis [21], and Water Footprint Models [22] reveal internal systemic linkages by examining resource flows and metabolic processes. Secondly, in identifying key influencing factors and barriers, spatial econometric models [1], barrier degree models [11,23], and gray correlation analysis [23] have been employed to diagnose critical shortcomings and driving factors constraining coordinated system development. Research consistently indicates that energy self-sufficiency rates, water resource utilization efficiency, and agricultural irrigation patterns represent critical bottlenecks affecting WEF system coordination [15,23,24]. Studies employing qualitative analysis, through literature reviews and comparative case studies, have provided in-depth interpretations of policy constraints, coordination opportunities, and governance challenges in WEF management across diverse regional contexts, offering crucial insights into systemic complexity [25–29].

Research focusing on Northeast China has provided a crucial foundation for this study while also revealing several areas warranting further exploration. Some scholars have assessed the coupling coordination degree [12,15], security risks [13], and efficiency matching [14] of the WEF system in the region, identifying key obstacles such as energy structure and water resource pressures [23,30]. However, existing research exhibits several limitations: On one hand, current studies often lack temporal dynamics, with most relying on cross-sectional data or short time series, failing to track the long-term evolution trends, phased characteristics, and turning point drivers of WEF system coupling coordination. On the other hand, these studies lack an in-depth analysis of spatial heterogeneity mechanisms. While provincial differences are noted, there is insufficient examination of the structural causes underlying these variations and how they interact through cross-system flows. Finally, insufficient attention is paid to system resilience. Few studies incorporate “resilience” as an independent, operationalized core dimension within the comprehensive evaluation framework of Northeast China’s WEF systems. Moreover, there is no systematic examination of how subsystem resilience should regulate the relationship between security and coordination, making it difficult to propose resilience enhancement strategies oriented toward long-term robust development.

This study addresses these gaps by constructing a three-dimensional (safety–coordination–resilience) evaluation framework and analyzing long-term panel data (2005–2023) using entropy weight, coupling coordination, and obstacle degree models. Its contributions are threefold: (1) It systematically analyzes the spatiotemporal evolution trajectory and phased characteristics of the coupling coordination degree within the Northeast China WEF system. (2) It conducts an in-depth diagnosis of the internal systemic barriers causing interprovincial divergence and their structural roots, with particular focus on the constraining effects of the energy subsystem and water resource utilization efficiency. (3) This paper empirically examines the critical mediating role of resilience dimensions within the WEF system, elucidating how resilience modulates the relationship between security and coordination. This provides new empirical evidence and theoretical perspectives for resource-based regions to achieve systematic governance and resilience enhancement under multiple pressures.

3. Overview of the Study Area and Data Sources

3.1. Overview of the Study Area

Northeast China is located in the northeastern part of China, between 118°53′ E to 135°05′ E longitude and 38°43′ N to 53°33′ N latitude, specifically encompassing the complete geographical unit formed by Heilongjiang, Jilin, and Liaoning provinces. The overall terrain of Northeast China is characterized by mountains surrounding three sides and an open plain in the central area, with a total area of approximately 788,000 square kilometers, serving as an important national territorial space and old industrial base in China. The main land use types are forestland and cultivated land, which possess both ecological functions and agricultural production advantages, making it a national resource-rich region and core grain-producing area. This region has a temperate continental monsoon climate, with long and cold winters and warm and rainy summers. Precipitation is mainly concentrated from June to August, and the average annual precipitation decreases from southeast to northwest, ranging from approximately 1000 mm in the Changbai Mountain area to about 400 mm in the western Songnen Plain. The general situation map of the study area is shown in Figure 1.

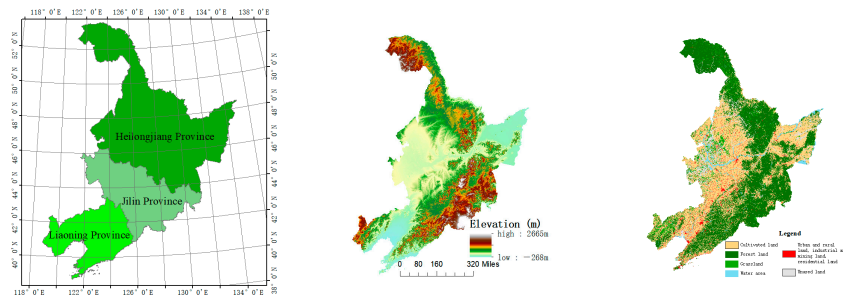


Figure 1. General Map of the Study Area.

3.2. Selection of Indicators and Data Sources

The WEF system is a complex, interconnected network. The scientific and standardized development of its assessment metrics is a key factor in measuring the coupling and coordination level of the WEF security system. The WEF's three components form a complex and interdependent system, meaning that when changes occur in one subsystem, they exert direct or indirect impacts on other subsystems through channels such as resource flows, policy interventions, and environmental feedback. This correlation is particularly pronounced in Northeast China due to its unique resource endowment, industrial heritage, and climate vulnerability. To understand the interactions among these three systems, it is necessary to construct a theoretical framework that reflects the internal security of each subsystem while also embodying cross-departmental synergies and the system's resilience against external shocks. To comprehensively evaluate the relevance of the WEF, this paper adopts an evaluation framework encompassing three dimensions—security, collaboration, and resilience—based on relational theory [5,7] and resilience thinking [31]. This framework addresses the need for an integrated assessment that transcends single-dimensional analysis [23].

Among this framework, security reflects the inherent stability and adequacy of each subsystem, serving to detect the true development status of water–energy–food systems in Northeast China. It encompasses resource availability, demand pressures, and supply–demand balance, forming the foundation for system operation. Synergy reflects the coordination and trade-off mechanisms within the WEF system, serving to measure resource conversion efficiency and inter-subsystem trade-offs. Its purpose is to address synergies and conflicts arising from competing uses, particularly the tensions between energy-intensive water use and agricultural water use, as well as between energy for pumping and food processing. Resilience reflects the feedback mechanisms within WEF systems, serving to evaluate a system's capacity to absorb disturbances, adapt to changing conditions, and recover from shocks. This dimension, representing a key innovation of this paper, is particularly critical for Northeast China, where climate variability, policy shifts, and economic transformation pose recurring threats to system stability.

This paper integrates the relevant literature [11,13,14,18,29] with the actual national conditions of Northeast China. By selecting 24 indicators to operationalize this framework, these metrics reflect both internal system security and dynamic inter-system relationships, forming a triple analytical framework of “state-connection-capability” (see Table 1 for details). Each assessment criterion level includes specific indicators for water systems, energy systems, and food systems, ensuring the comprehensiveness and systematic nature of the evaluation. Water system indicators comprise A1, A2, A3, B1, B5, C1-1, C2-1, and C3-3; energy system indicators cover A4, A5, A6, B2, B3, C1-3, C2-2, and C3-2; while food system indicators are A7, A8, A9, B4, B6, C1-2, C2-3, and C3-1. The inclusion of water-saving irrigation rate (C2-1) and energy self-sufficiency rate (C1-3) specifically aims to evaluate key leverage points for enhancing coordination and resilience. By integrating

these three dimensions, the framework presented in this paper enables a diagnostic assessment of system strengths, bottlenecks, and cross-scale interactions, thereby providing a solid foundation for the design of differentiated policies.

Table 1. Comprehensive Indicator System for the WEF System in Northeast China.

Criterion Layer	Primary Indicator Layer	Secondary Indicator Layer	Formula/Unit	Direction	Weight
Security	Water Resources Subsystem	A1: Per Capita Water Resources	Total water resources/Permanent population (m^3/person)	+	0.046
	Water Resources Subsystem	A2: Per Capita Water Use	Total water use/Permanent population (m^3/person)	−	0.095
	Water Resources Subsystem	A3: Water Resource Utilization Rate	Total water use/Total water resources (%)	−	0.043
	Energy Subsystem	A4: Per Capita Energy Production	Total energy production/Permanent population (tce/person)	+	0.076
	Energy Subsystem	A5: Per Capita Energy Consumption	Total energy consumption/Permanent population (tce/person)	−	0.035
	Energy Subsystem	A6: Elasticity Coefficient of Energy Consumption	Growth rate of energy consumption/Growth rate of GDP (%)	−	0.041
	Food Subsystem	A7: Per Capita Cultivated Land Area	Cultivated land area/Permanent population (m^2/person)	+	0.064
	Food Subsystem	A8: Grain Yield per Unit Area	Total grain output/Sown area of grain crops (kg/hm^2)	+	0.020
	Food Subsystem	A9: Grain Output Fluctuation Rate	$\frac{ \text{Actual output in year } t - \text{Trend output in year } t }{\text{Trend output in year } t} \times 100\%$	−	0.019
Coordination	Water–Energy Nexus	B1: Water Consumption per Unit GDP	Total water use/GDP ($\text{m}^3/10^4 \text{ CNY}$)	−	0.052
	Water–Energy Nexus	B2: Water Consumption per Unit Energy Production	Industrial water use/Total energy production (m^3/tce)	−	0.030
	Energy–Food Nexus	B3: Total Agricultural Machinery Power per Unit Area	Total power of agricultural machinery/Total sown area of crops (kW/hm^2)	+	0.029

Resilience	Energy–Food Nexus	B4: Proportion of Effective Irrigated Area	Effective irrigated area/Cultivated land area (%)	+	0.021
	Water–Food Nexus	B5: Proportion of Agricultural Water Use	Agricultural water use/Total water use (%)	–	0.043
	Water–Food Nexus	B6: Water Consumption per Unit Grain Output	Agricultural water use/Total grain output (m ³ /kg)	–	0.055
	Coping Capacity	C1-1: Per Capita Grain Availability	Total grain output/Permanent population (kg/person)	+	0.060
	Coping Capacity	C1-2: Total Reservoir Storage Capacity	(10 ⁸ m ³)	+	0.015
	Coping Capacity	C1-3: Energy Self-Sufficiency Rate	Total energy production/Total energy consumption (%)	+	0.078
	Recovery Capacity	C2-1: Proportion of Water-Saving Irrigated Area	Water-saving irrigated area/Effective irrigated area (%)	+	0.052
	Recovery Capacity	C2-2: Growth Rate of Rural Electricity Consumption	(Current year's consumption—Previous year's consumption)/Previous year's consumption (%)	+	0.010
	Recovery Capacity	C2-3: Multiple Cropping Index	Total sown area of crops/Cultivated land area (%)	+	0.036
	Adaptive Capacity	C3-1: Comprehensive Agricultural Mechanization Level	Mechanized plowing area/Cultivated land area (%)	+	0.014
	Adaptive Capacity	C3-2: Proportion of Coal Consumption	Coal consumption/Total energy consumption (%)	–	0.041
	Adaptive Capacity	C3-3: Area of Soil Erosion Control	(10 ⁴ hm ²)	+	0.025

Note: “+” denotes a positive indicator (higher value is better); “–” denotes a negative indicator (lower value is better). tce = ton of standard coal equivalent.

This article takes Heilongjiang, Jilin, and Liaoning provinces as the reference research base, and the time period is 19 years (2005–2023). Except for the two indicators of the total water storage (C1-2) and the area of water and soil conservation (C3-3) directly taken from the China Statistical Yearbook, the remaining indicators were calculated in detail (see Table 1). The data used to calculate these indicators is primarily sourced from the China

Statistical Yearbook, China Water Resources Bulletin, China Energy Statistical Yearbook, and the statistical yearbooks of each province. For certain indicators where updated data is temporarily unavailable, the interpolation method has been applied as a substitute.

4. Research Methodology

4.1. Entropy Weight Method

The entropy weight method is an objective weighting technique based on the degree of dispersion inherent in the data. A greater dispersion for an indicator signifies a larger amount of information it provides, consequently leading to a higher assigned weight in the evaluation [32]. This study applied this method to standardize the relevant indicators and calculate their weights for assessing WEF system security.

Step 1: Data Standardization. To eliminate incomparability arising from differences in the dimensions and scales of various evaluation indicators, the original data were standardized to obtain dimensionless values.

For positive indicators:

$$x_{ij}' = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \quad (1)$$

For negative indicators:

$$x_{ij}' = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \quad (2)$$

where (x_{ij}) represents the original value of the (i) -th sample for the (j) -th indicator; $(\max(x_j))$ and $(\min(x_j))$ are the maximum and minimum values of the (j) -th indicator across all samples, respectively; and (x_{ij}') is the standardized value.

Step 2: Determination of Information Entropy $((e_j))$.

$$e_j = -\frac{1}{\ln(m)} \sum_{i=1}^m p_{ij} \ln(p_{ij}) \quad (3)$$

$$p_{ij} = \frac{x_{ij}'}{\sum_{i=1}^m x_{ij}'} \quad (4)$$

where (p_{ij}) is the proportion of the (i) -th sample for the (j) -th indicator, and (m) is the total number of study regions.

Step 3: Determination of Indicator Weights $((w_j))$.

$$w_j = \frac{g_j}{\sum_{j=1}^n g_j} \quad (5)$$

$$g_j = 1 - e_j \quad (6)$$

where (g_j) is the divergence coefficient.

4.2. Comprehensive Security Index

On the basis of the WEF system evaluation index system constructed in this paper and the determined weights, the weighted sum model of safety, coordination and resilience principles is used to calculate the safety index of water, energy, food and WEF systems, so as to evaluate the development level of each component.

Step 1: Calculate the security index for each subsystem.

$$S_k = U_k = \sum_{j=1}^n w_j \cdot x_{ij}' \quad (k = 1, 2, 3) \quad (7)$$

Here U_k represents the comprehensive development index of the k -th subsystem, S_k represents the safety index of the k -th subsystem—namely, the water system, energy system, and food system. w_j represents the weight of the corresponding index, and n represents the number of indicators in the subsystem.

The security index S_k of each subsystem is equivalent to its comprehensive development index U_k . This equivalence stems from the fully constructed evaluation framework, where security assessment is embedded within a multidimensional indicator system.

Step 2: Calculate the total system security index.

$$S = \sum_{k=1}^3 (W_k \times S_k) \quad (8)$$

In this formula, (S) represents the total safety index of the system, and (W_k) represents the weight of the (k) th subsystem. In order to reflect the synergistic evolutionary relationship within the water–energy–food network, the weights of the three subsystems are set to be equal, i.e., $(W_k = 1/3)$.

4.3. Coupling Coordination Degree Model

Coupling refers to the degree of interaction between two or more systems. It can describe the mutual influence among the water, energy, and food subsystems. Based on the coupling theory and previous studies [33,34], the specific calculation formula is as follows:

Step 1: Calculate the coupling degree (C) .

$$C = \left[\frac{U_1 \cdot U_2 \cdot U_3}{\left(\frac{U_1 + U_2 + U_3}{3} \right)^3} \right]^{1/3} \quad (9)$$

In this case, the range of coupling degree (C) is $[0, 1]$. When $(C = 0)$, it indicates that the systems are independent and tend to the state of disorder; $(C = 1)$ means that there is a positive resonance state between the systems, and the new ordered structure is developing in a positive direction.

Step 2: Calculate the coupling coordination degree (D) .

$$D = \sqrt{C \cdot T} \quad (10)$$

$$T = \alpha U_1 + \beta U_2 + \gamma U_3 \quad (11)$$

In the equations, (D) represents the degree of coupling coordination, and (T) is the comprehensive development evaluation index of the water–energy–food (WEF) system. The coefficients (α) , (β) and (γ) reflect the relative importance of each subsystem. This study believes that the three subsystems are equally important, so the setting is $(\alpha = \beta = \gamma = 1/3)$.

Finally, in order to visually evaluate the coordination status of water, energy and food systems, and combined with relevant research conclusions [35–38], this paper divides the coupling coordination degree (D) into eight levels, as shown in Table 2.

Table 2. Classification Criteria for Coupling Coordination Degree Levels.

Coupling Coordination Degree (D)	Coordination Level	Coupling Degree Stage
$0.00 \leq D < 0.20$	Extreme Dysfunction (I)	Low-Level Coupling
$0.20 \leq D < 0.40$	Severe Dysfunction (II)	Low-Level Coupling
$0.40 \leq D < 0.50$	Near Dysfunction (III)	Antagonistic Stage
$0.50 \leq D < 0.60$	Primary Coordination (IV)	Running-in Stage

$0.60 \leq D < 0.70$	Intermediate Coordination (V)	Running-in Stage
$0.70 \leq D < 0.80$	Good Coordination (VI)	Running-in Stage
$0.80 \leq D < 0.90$	High-Quality Coordination (VII)	High-Level Coupling
$0.90 \leq D \leq 1.00$	Superior Coordination (VIII)	High-Level Coupling

4.4. Obstacle Degree Model

The degree of disability model is a diagnostic mathematical model based on the deviation of individual indicators from the optimal value. The principle of this model is to effectively identify the key weak links that need to be improved by quantifying the degree to which each indicator deviates from the coordinated development goal of the system. The purpose of the calculation of the model is to provide an accurate entry point for policy intervention and enhance the synergy of the whole system. This method is widely adopted in relevant research [39–42].

The model follows the logical chain of first calculating the degree of index deviation, then calculating the factor contribution rate, and finally derivating the severity of the obstacle. The specific calculation steps are as follows.

Step 1: Calculate the indicator deviation (O_{ij}).

$$O_{ij} = 1 - X_{ij}' \quad (12)$$

In the formula, (X_{ij}') represents the standardized value of the j -th indicator of the i th evaluation unit, and the value range is $[0, 1]$. The higher (O_{ij}) value indicates that the gap between the current state of the indicator and the ideal state is larger.

Step 2: Calculate the factor contribution (F_j).

$$F_j = W_j \quad (13)$$

In this formula, (W_j) represents the index weight determined in the process of constructing the indicator system and is directly used as its contribution.

Step 3: Calculate the obstacle degree (M_{ij}).

$$M_{ij} = \frac{O_{ij} \times F_j}{\sum_{j=1}^n (O_{ij} \times F_j)} \times 100\% \quad (14)$$

Here, (n) represents the total number of indicators. The degree of disability (M_{ij}) ranges from 0% to 100%. The higher the (M_{ij}) value, the greater the indicator is an obstacle to the realization of high-level linkage and coordinated development, so it is recognized as a key obstacle.

5. Results and Analysis

5.1. Development Level of the WEF Security System in Northeast China

5.1.1. Analysis of the Comprehensive Development Level

As shown in Table 3, from 2005 to 2023, the overall security level of the WEF system in Northeast China exhibited a clear phased trend: an initial period of fluctuation and decline, followed by a phase of relative stability, and finally a gradual recovery. The regional average security score decreased from 0.463 in 2005 to 0.365 in 2014, before recovering to 0.501 in 2023, representing a net increase of approximately 8.2% over the entire period.

Temporally, the evolution of the security level in Northeast China can be divided into three distinct stages: Between 2005 and 2014, the security level experienced fluctuations with an overall downward trend. Affected by industrial restructuring and climate change pressure, the average decreased from 0.463 to 0.365. From 2015 to 2019, it entered the stage of adjustment and recovery. With the promotion of policy support and ecological

protection, the value gradually increased from 0.410 to 0.486. After 2020, facilitated by advancements in water-saving technologies, energy efficiency, and grain production systems, the security level showed steady improvement, and the average has exceeded 0.50. This phased development pattern aligns with findings from studies of WEF systems in other regions. Research by Chang et al. [1] and Wang et al. [10] similarly indicates that WEF systems experience policy-driven recovery following initial fluctuations.

Spatially, significant disparities in security levels were observed among the three northeastern provinces. This significant disparity in interprovincial development levels indirectly corroborates the widespread phenomenon of uneven WEF system development at the national scale, as highlighted in the research by Han et al. [42]. Heilongjiang Province has always maintained a leading position and performed relatively stably, exceeding 0.62 from 2009 to 2011 and from 2019 to 2020. Although there was a temporary decline in 2023, it then rebounded to 0.588. Liaoning exhibited the greatest volatility, with its score plummeting to a low of 0.303 in 2009 and again to 0.230 in 2014. Although it recovered to 0.432 by 2023, it consistently remained the lowest among the three provinces, indicating lower systemic stability. Meanwhile, Jilin Province was at a medium level as a whole, showing a steady upward trend from 2005 to 2023, with a final score of 0.484.

Table 3. Comprehensive Development Level of the WEF Security System in Northeast China.

Province	Heilongjiang	Liaoning	Jilin	Regional Average
2005	0.518	0.527	0.345	0.463
2006	0.567	0.399	0.293	0.420
2007	0.526	0.363	0.386	0.425
2008	0.531	0.378	0.396	0.435
2009	0.626	0.303	0.419	0.450
2010	0.655	0.494	0.503	0.550
2011	0.647	0.476	0.410	0.511
2012	0.496	0.363	0.445	0.435
2013	0.466	0.378	0.414	0.419
2014	0.495	0.230	0.368	0.365
2015	0.506	0.323	0.401	0.410
2016	0.510	0.409	0.427	0.448
2017	0.499	0.353	0.416	0.423
2018	0.566	0.386	0.421	0.458
2019	0.622	0.392	0.445	0.486
2020	0.641	0.396	0.485	0.507
2021	0.585	0.425	0.431	0.480
2022	0.567	0.443	0.466	0.492
2023	0.588	0.432	0.484	0.501

5.1.2. Analysis of Development Levels Across WEF Security Subsystems

Northeast China as a whole has formed a development model centered on the grain system, with significant fluctuations in the water resources system and sustained pressure on the energy system. The development level of each subsystem shows the uneven characteristics as shown in Figure 2. This grain-centric model is attributable to Northeast China's role as a national primary grain-producing region, whose developmental trajectory is heavily reliant on its agricultural sector. This finding is corroborated in the article by Lu et al. [22].

From the perspective of inter-system differences, the grain subsystem has maintained a relatively advanced level of development, as the basis for supporting the development of the regional system, especially after 2021. The water resources subsystem ranks second,

but shows significant annual volatility, which has become the main factor in short-term system fluctuations. The energy subsystem is still relatively weak and faces greater pressure in a specific period, which has become an important bottleneck that restricts the overall development level of the region. The significant fluctuations observed in the water resources subsystem align with vulnerability findings noted by Li et al. [12] in studies of arid and semi-arid regions. The dominant role of the food subsystem in supporting overall system development also corresponds with the function of resource-intensive agriculture discussed by Feng et al. [19] in their research. These consistencies lend external validity to the study's findings regarding subsystem disparities.

From the perspective of inter-provincial differences, the specific development of the three systems in the three provinces in the northeast can be divided into the following situations. The development level of the three subsystems in Heilongjiang Province is shown in Figure 2B. Relying on the status of commodity grain production base, black soil resources, and scientific and technological investment advantages, the province's score of the food security subsystem has steadily improved from 0.10 in 2005 to 0.906 in 2023, laying a solid foundation for supporting the development of high-level systems. The regional water safety subsystem fluctuates due to the influence of climate and agricultural water use, and its value fluctuates sharply between 0.028 and 0.454, which has become the main factor in the annual change in the comprehensive development level of the province. The energy security subsystem in the region is usually maintained in the high range of 0.517 to 1.0, providing basic support for the system.

The development level of the three subsystems in Liaoning Province is shown in Figure 2C. The water resources safety subsystem is better than the other two provinces in most years, and its peak occurred in 2010, 2016, and 2020, respectively. This result is due to relatively perfect water conservancy facilities and effective industrial water management. However, due to the limited availability of total resources, it has decreased year by year since then. The energy security subsystem is the most vulnerable system, with a sharp drop from 0.372 in 2005 to 0.034 by 2020. Since then, although there has been a slight recovery, the overall level is still at a low level, reflecting the severe challenges faced in the process of energy structure transformation that oppress the sustainable development of traditional industrial areas. The food security subsystem has been at a low level for a long time, indicating that its foundation is relatively fragile.

The development level of each subsystem in Jilin Province is shown in Figure 2D. The two subsystems of water security and food security have shown a coordinated and stable upward trend, from 0.677 and 0.357 in 2005 to 0.590 and 0.565 in 2023, forming a mutually supportive relationship. However, the energy security subsystem has been at a low level for many years, fluctuating between 0.1 and 0.3 in most years, which has become an important bottleneck to fully release the advantages of water and food resources in Jilin Province.

The analysis reveals that resilience indicators play a crucial moderating role in the development trajectories of provincial subsystems. Heilongjiang Province's steady developmental rise is primarily attributable to its high and annually improving resilience. This is evident in key indicators: Per Capita Grain Availability (C1-1) remained consistently high (0.8–1.0 kg/person from 2015 to 2023), and the Comprehensive Agricultural Mechanization Level (C3-1) stabilized around 65%. This robust resilience effectively buffered the system against fluctuations in water resources. In contrast, Liaoning Province's weak energy subsystem resilience—epitomized by a low Energy Self-Sufficiency Rate (C1-3, at 0.62%)—led to a slow recovery from industrial restructuring policies. Conversely, Jilin Province demonstrated outstanding adaptive resilience. Its Proportion of Water-Saving Irrigated Area (C2-1) expanded from approximately 20% to 60%, providing stable support for coordinated water-grain development.

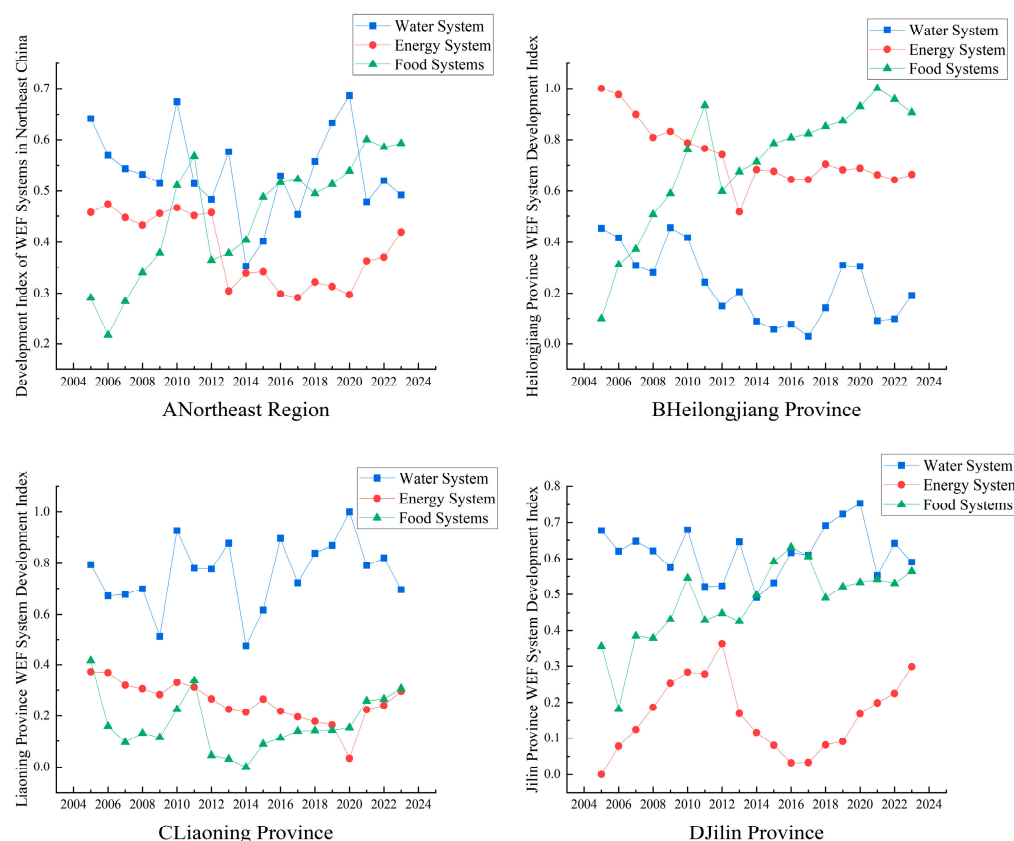


Figure 2. Trends in Development Levels of Water Systems, Energy Systems, and Food Systems in Northeast China.

5.2. Coupling Coordination Analysis of the WEF Security System in Northeast China

5.2.1. Analysis of Coupling Coordination Degree

The Coupling Coordination Degree (CCD) of the WEF system in Northeast China exhibited a fluctuating upward trend, rising from 0.457 in 2005 to a peak around 2010, before declining to a trough of 0.405 in 2014. Subsequently, it recovered gradually to 0.670 by 2023. Although significant divergence was observed among the three provinces around 2014, their CCD had all recovered to above 0.63 by 2023, indicating a converging trend and a complex interactive process among subsystems evolving from dysfunction towards synergy, as detailed in Figure 3. This pattern of increasing convergence in coupled-coordinated volatility is also observed in the Yangtze River Delta region studied by Zhang et al. [33], though driven by different factors.

From the perspective of time, the process of improving the level of WEF'S CCD can be summarized into three stages. The first stage of this level of development showed a relatively coordinated trend from 2005 to 2010, and showed the characteristics of early differentiation. Driven by the regional revitalization policy, Heilongjiang Province has maintained a high degree of coordination, and Jilin Province has achieved steady improvement. At the same time, Liaoning Province still maintains a coordinated state under the pressure of energy. Its second stage was characterized by severe dysfunction and in-depth adjustment from 2011 to 2017, of which 2013 to 2014 became a turning point in development. The strict national environmental policy has had an impact on Liaoning Province, and its linkage degree plummeted to 0.068. Heilongjiang Province and Jilin Province are also in trouble due to fluctuations in water resources and agricultural policy adjustments. The pronounced divergence around 2014 highlights the basin ecosystem's high sensitivity to stringent environmental policy shocks, a phenomenon confirmed by

the analysis of Xian et al. [14] and Zhang et al. [43] from a supply–demand security perspective, further indicates that policy interventions serve as a core driver reshaping the coupling relationships within the WEF system, leading to divergences in coordination levels across regions. Its third stage is from 2018 to 2023, which can be summarized as the trend of slow recovery and coordinated reconstruction. With the implementation of policy absorption and the promotion of systematic measures, Heilongjiang Province and Jilin Province have achieved a relatively coordinated, rapid recovery, while Liaoning Province has entered a difficult long-term recovery process.

From the perspective of spatial distribution, there are significant differences in the WEF's CCD development models of these three provinces. The CCD of WEF system in Heilongjiang Province has always maintained a high level of adjustment. According to Figure 3B, it can be seen that the value of most years in the province exceeds 0.63, up to 0.794, showing strong system stability and toughness. The level of WEF's CCD in Liaoning Province shows the most significant fluctuations. According to Figure 3C, the province's adjustment showed a slow upward trend after bottoming out in 2014, reaching 0.631 by 2023, but still lower than the initial level. The level of WEF's CCD in Jilin Province shows a steady upward trend, located between Heilongjiang Province and Liaoning Province. As shown in Figure 3D, while the food system continues to improve, the water system remains relatively stable, and the degree of synergy has steadily increased from 0.453 to 0.681. The phenomenon of inter-provincial differences in the CCD of the WEF system vividly shows the complex interaction between policy impact, resource endowment superiority, and regional resilience.

Provincial data underscore that system resilience is a critical determinant of coupling coordination stability. In Heilongjiang, despite substantial water resource volatility, the high buffering capacity of its resilient food subsystem has enabled the WEF system to maintain a high level of coupling coordination. Conversely, Liaoning's low energy subsystem resilience—compounded by the subsystem's intrinsic security deficits—undermines overall coordination through the water–energy nexus. In contrast, Jilin Province, by strengthening the recovery and adaptive capacity within its water–food nexus, has fostered synergistic effects that cascade across all three subsystems.

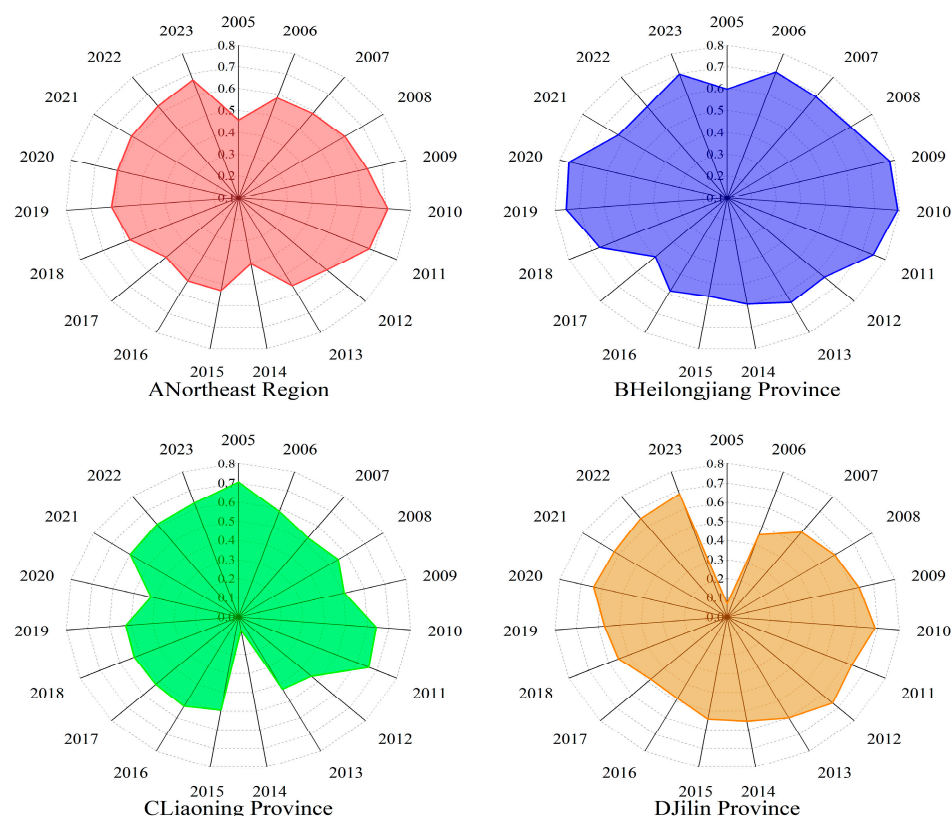


Figure 3. Trend in Coupling Coordination of WEF Security Systems in Northeast China.

5.2.2. Analysis of Coupling Coordination Degree Levels

Between 2005 and 2023, the overall CCD of the WEF system in Northeast China evolved from the Near Dysfunction stage (III) to the Intermediate Coordination stage (V), marking a pivotal shift from the conflict to the coordination. As shown in Figure 4, it is not a straight upward process, but a fluctuating upward trend.

Through the analysis of the changes in the level of coupling and coordination over time, the development path of different provinces is revealed. The coupling and coordination level of Heilongjiang Province maintained a high CCD for most of the research period, fluctuating between Primary (IV) and Good (VI) Coordination. Since then, it entered a phase of fluctuation adjustment from 2012 to 2017. The main reason is that the region has been affected by policy adjustments such as water resource fluctuations, the restructuring of the agricultural structure, and climate change. The adjustment capacity has continued to decline. By 2017, it is close to the stage of Near Dysfunction (III). Its development level from 2018 to 2023 can be summarized as the final recovery and strengthening period. With the improvement of hydrological conditions and the adjustment of agricultural structure adaptability, the adjustment level gradually recovers to above the Intermediate Coordination (V). The ability of Heilongjiang to maintain relatively high coordination despite water resource fluctuations underscores the stabilizing effect of a robust food subsystem, a buffer effect that is supported by the findings of Zhang et al. [35] in major grain-producing regions.

The CCD of the WEF system in Liaoning Province exhibited the most pronounced fluctuations, undergoing a complete cycle of high-level linkage, a sharp decline, and a long-term recovery. In 2014, the energy subsystem of Liaoning Province was severely impacted by strict national environmental policies, including the Action Plan for the Prevention and Control of Atmospheric Pollution, resulting in a sharp decline in its WEF coordination level, and finally falling into Extreme Dysfunction (I, $D = 0.068$). At the same time,

the food subsystem failed to play an effective buffering role. Since 2015, the energy system of Liaoning Province has gradually entered a stage of slow recovery under the impetus of industrial restructuring and policy support. By 2023, the CCD of its WEF system had recovered to the Primary Coordination (IV). It is worth noting that its recovery has slowed down significantly compared with the previous recession. This pattern of severe, prolonged disruption exemplifies the challenges faced by traditional industrial bases during green transitions, where rigid energy systems can critically impede broader synergistic mechanisms within the WEF nexus, as noted by Cai et al. [23]. The WEF system in Liaoning Province is characterized by energy self-sufficiency rates emerging as a key limiting factor, while economic structural lag and technological innovation deficits exacerbate transformation challenges. These factors have been repeatedly validated as primary obstacles to coordinated WEF development in studies by Zhang et al. at the Yellow River basin scale [43] and Zhang et al. at the national scale [44].

The level of WEF system coupling coordination degree in Jilin Province showed a steady upward trend, from Extreme Dysfunction (I) in 2005 to Intermediate Coordination (V) in 2023. This progress unfolded in three discernible phases: low-level combination, rapid rise, and stability and strengthening. This sustained progress was driven by two key factors. One of the reasons is the continuous improvement and stability of its food subsystem, and the water supply system also constitutes the main support of the WEF system. On the other hand, the most important reason is that Jilin Province has gradually improved the energy subsystem through the development of new energy, jointly propelling the steady advancement of systemic coordination. The very different evolution paths of these three provinces reveal the complex interaction between internal resource structure, policy response and external shocks, and provide a basis for differentiated systematic coordination.

This study finds that fluctuations in subsystem security directly drive changes in CCD. The case of Liaoning illustrates this, the sharp decline in energy subsystem security (particularly the C1-3 Energy Self-Sufficiency Rate) during 2013–2014 directly caused its CCD to plummet to the Extreme Dysfunction (I). In contrast, Jilin Province demonstrated a steady improvement in grain subsystem security, providing a solid foundation for the sustained enhancement of its intermediate coordination level. This indicates that security serves as the cornerstone of coordination; deterioration in coupling coordination typically manifests first as the collapse of security in a critical subsystem. Therefore, maintaining subsystem security levels—particularly the stability of key barrier factors—is a prerequisite for enhancing the overall synergistic capacity of the WEF system.

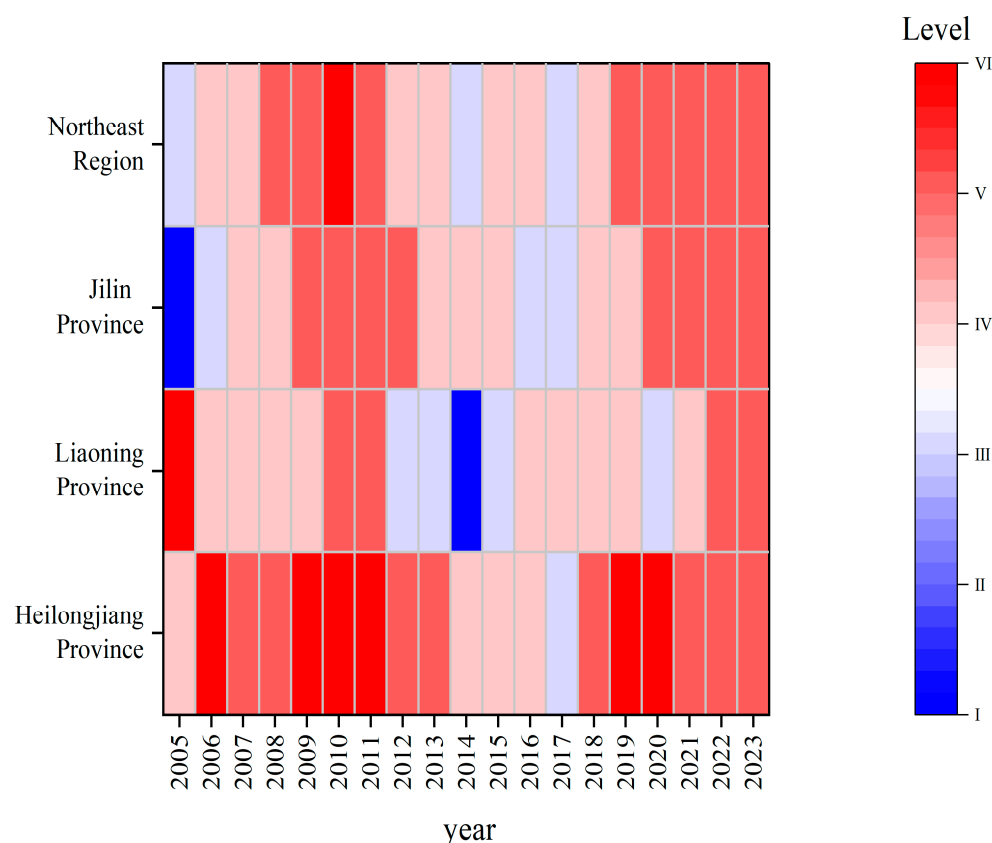


Figure 4. Trend in WEF Security System Coupling Coordination Levels in Northeast China.

5.3. Research on Obstacle Factors Affecting the Coordinated Development of the WEF Security System in Northeast China

5.3.1. Analysis of Obstacle Factors at the System Level

The primary obstacles to WEF coordinated development in Northeast China lies within the energy subsystem, with the water resources subsystem constituting a secondary, yet significant, constraint. As shown in Figure 5, the model also shows significant step-by-step fluctuations and obvious inter-provincial structural differences.

From the perspective of time, the obstacle structure of each WEF subsystem in Northeast China has been strongly influenced by policy interventions and climate variability, and the research period can be divided into three stages. The first stage of the WEF system in Northeast China is from 2005 to 2012, which can be summarized as the accumulation and fluctuation period, and the barriers in the energy and water resources subsystems are on the rise alternately. Between 2009 and 2011, it was affected by the fluctuation of precipitation and the demand for agricultural water, and the obstacles to the use of water resources were significantly aggravated. The second stage is 2013–2017, which can be summarized as a period that marks a significant policy impact. Under the constraints of strict environmental protection regulations such as the Action Plan for the Prevention and Control of Atmospheric Pollution (referred to as the Ten Measures), the operating obstacles of the energy subsystem are forced to continue to intensify, especially from 2014 to 2016, and eventually evolving into the main bottleneck that hinders the scheduling of the system. The third phase (2018–2023) transitioned into an adjustment and partial recovery. With the implementation of energy-saving renovations and structural optimization, the energy obstacle degree decreased slightly, and the food subsystem obstacle degree generally declined slowly and steadily. However, the water resources obstacle degree experienced periodic rebounds due to climatic fluctuations and issues related to water-use efficiency.

Regarding interprovincial disparities, the obstacle structures of the three provinces are closely tied to their respective resource endowments, industrial positioning, and policy responses. The degree of water resource barriers in Heilongjiang Province is relatively prominent, which is caused by its large-scale agricultural irrigation and climate sensitivity. The level of energy barriers in the region is generally lower than that of Liaoning Province and Jilin Province, showing an upward trend since 2020, which also shows that the transformation of clean energy is still facing continuous challenges. As a traditional heavy industry base, the obstacle degree of the energy subsystem in Liaoning Province has been maintained at a high level for many years, exceeding 40% in most years, and continued to remain above 43% from 2013 to 2020. This highlights the great pressure facing the province in energy transformation. The prominence of energy subsystem constraints, particularly in industrialized Liaoning, aligns with findings on the challenges faced by similar legacy industrial bases in achieving coordinated development. Research conducted by Hao et al. [11] and Xian et al. [14] similarly suggests that transforming the energy structure is the main obstacle to achieving coordinated development. The barrier structure of the WEF system in Jilin Province is more balanced. The province's water resources barriers are also at a high level due to the competition and utilization efficiency of industrial water. Its energy obstacle degree rose sharply around 2020, peaking at 47.75%, reflecting the challenges of integrating new energy sources while managing the phase-out of traditional ones. On the contrary, the failure rate of the food subsystem is generally on a downward trend, indicating that agricultural stability is gradually improving.

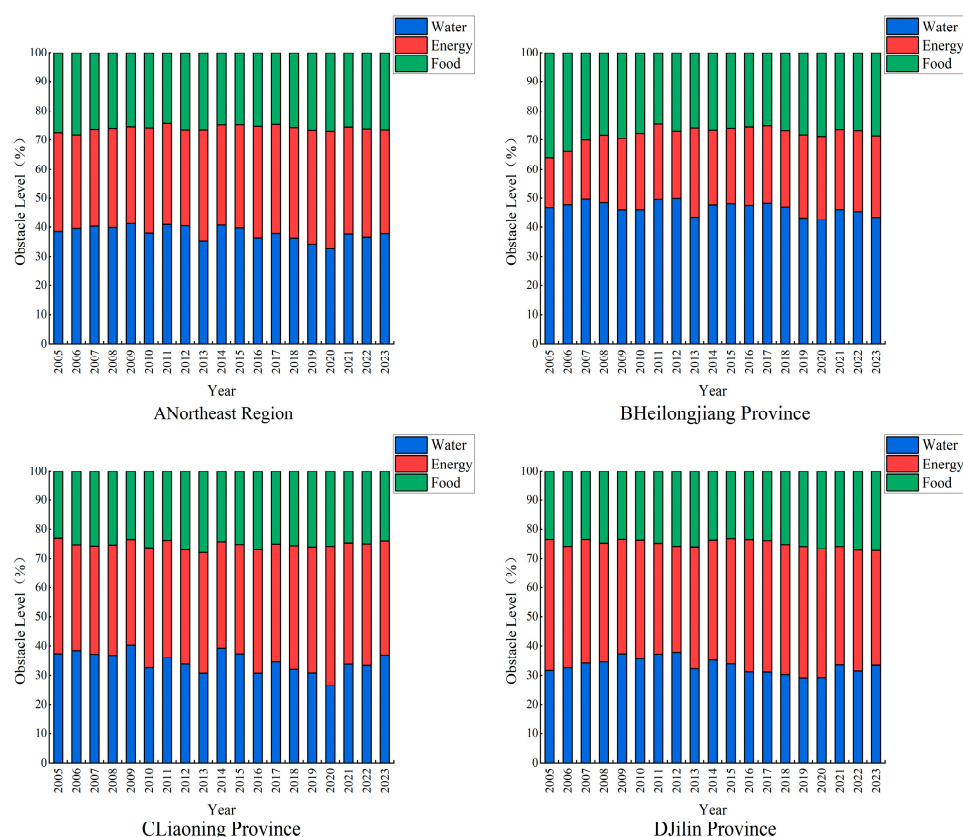


Figure 5. Barrier Degree Results for Water Systems, Energy Systems, and Food Systems in Northeast China.

5.3.2. Analysis of Obstacle Factors at the Indicator Level

The main obstacle to coordinated WEF development in Northeast China is the pervasive structural weakness of the energy subsystem, primarily reflected in the deficiencies

of indicators C1-3 (Energy Self-Sufficiency Rate) and A4 (Per Capita Energy Production). Chang et al. [13] identified the energy self-sufficiency rate (E10) and electricity generation (E3) as “high-barrier-high-drive” variables—meaning they are not only critical bottlenecks but also key leverage points for systemic improvement—in studies of the regional WEF nexus. Therefore, addressing the energy subsystem’s bottlenecks is essential for enhancing overall coordination. Secondary yet significant obstacles are found in indicators like A2 (Per Capita Water Use), A7 (Per Capita Cultivated Land Area), C1-1 (Per Capita Grain Availability), and C2-1 (Proportion of Water-Saving Irrigated Area). The prominence of these indicators underscores the tight inter-subsystem linkages, where energy constraints can ripple through to hinder water and food security. Therefore, according to the image display and specific index values in Figure 6, it can be concluded that the model is characterized by the significant existence of structural weaknesses, obvious inter-system effects, and the complexity of interrelated regional characteristics.

From the perspective of time, the changes in important obstacles of the WEF system reflect the three stages of the shifting policy focus. During the period of dominant growth from 2005 to 2012, the obstacles in Northeast China were mainly concentrated on indicators related to resource abundance and basic efficiency. During the period of severe environmental constraints from 2013 to 2017, national policy intervention intensified the resource competition between subsystems in the region, further exacerbating the barriers to relevant indicators, such as A2 (Per Capita Water Use) and C1-3 (Energy Self-Sufficiency Rate). In the subsequent stage of system recovery and resilience construction, that is, from 2018 to 2023, due to the policy shift to building multi-dimensional resilience, the attention of indicators related to long-term adaptability such as C2-1 (Proportion of Water-Saving Irrigated Area) and C3-2 (Proportion of Coal Consumption) in the region was further increased. This development shows that the coping approach has shifted from addressing symptoms to strengthening basic capabilities. The evolution of key obstacles from resource endowment to management efficiency reflects a maturing policy focus, a shift that aligns with the broader trajectory of WEF nexus governance discussed by Hejnowicz et al. [26]. Studies by REN et al. in arid regions reveal similar trends [45]. They show that transitioning from static evaluation to dynamic prediction and optimized management has established a foundation for long-term, efficiency-driven management. This approach assesses and forecasts the level of coupling coordination in arid areas.

From the perspective of spatial distribution, the characteristics of important obstacles show significant inter-provincial differences. The obstacles of the WEF system in Heilongjiang Province are shown in Figure 6B. The main problems are reflected in the changing limiting factors in the water, grain, and energy systems. The indicators related to the main obstacles include A1, A2, B1, B6, C1-1, C1-3, and C2-1, among which A2 (per capita water consumption) and B6 (unit grain production water consumption) are particularly prominent. Under the influence of the policy, Liaoning Province shows the characteristics of systematic response and correlation breakage. As shown in Figure 6C, the obstacles are concentrated in indicators such as A4, A7, C1-1, and C1-3. Jilin Province faces challenges in stability and related efficiency in the follow-up development model. According to Figure 6D, it can be concluded that the main obstacles in the province are concentrated in indicators such as A4, A7, C1-3, and C2-1.

Analysis of key obstacle factors reveals that the resilience dimension plays a crucial mediating role in provincial subsystem development. Heilongjiang Province’s stable performance stems from its robust strain capacity (e.g., consistently maintaining high C1-1 Per Capita Grain Availability) and adaptive capacity (e.g., stable C3-1 Comprehensive Agricultural Mechanization Level), which effectively mitigate the impact of water resource fluctuations. In contrast, Liaoning Province’s overall WEF system recovery remains sluggish, with the energy subsystem’s weak resilience—evident in severely inadequate of

C1-3 Energy Self-Sufficiency Rate—exacerbating this challenge. Jilin Province’s steady progress stems from enhanced recovery capacity, reflected in the significant increase in C2-1 Proportion of Water-Saving Irrigated Area.

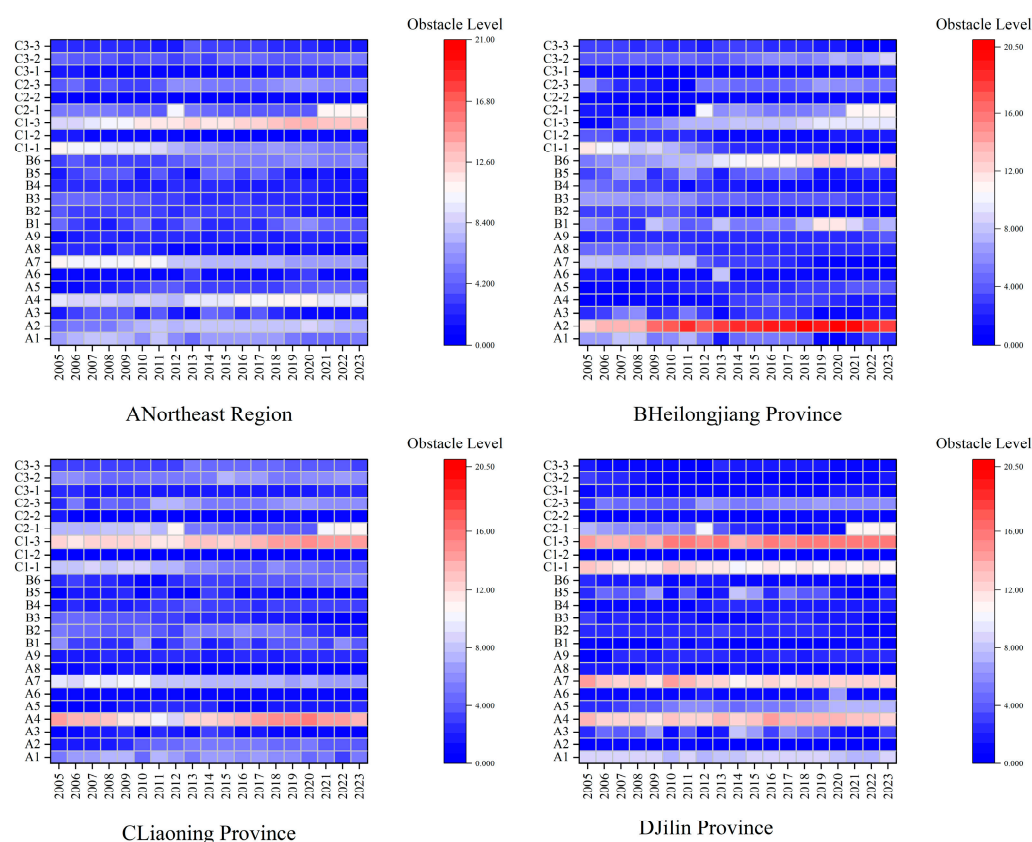


Figure 6. Barrier Levels for the Collaborative Development of WEF Security Systems in Northeast China.

6. Conclusions and Policy Implications

6.1. Conclusions

Based on the three-dimensional evaluation index system covering safety, coordination, and resilience, this study analyzed 19-year panel data (2005–2023) for Northeast China. The entropy weight method was employed to assign weights to indicators, and the spatial–temporal evolution of the WEF system was systematically examined using a comprehensive security index, a coupling coordination degree (CCD) model, and an obstacle degree model.

(1) The comprehensive development level of the WEF system in Northeast China exhibited a fluctuating upward trend, progressing to a stage of moderate coordination with an overall increase of approximately 8% during the study period. Significant inter-provincial disparities persist, forming three distinct regional patterns. Heilongjiang maintained a stable, leading position backed by solid food security; Jilin demonstrated steady growth; and Liaoning remained at a relatively low and volatile level, constrained by its energy transition and grain production. Subsystem development was also uneven, dominated by food security but challenged by volatile water resources and a high-pressure energy subsystem.

(2) The coupling coordination degree (CCD) evolved from initial divergence to gradual convergence, improving overall despite fluctuations. A key finding is the bidirectional reinforcement mechanism between subsystem security and CCD. Security acts as the

foundation for coordination, as evidenced by the rapid decline in Liaoning's CCD following a collapse in energy subsystem security due to policy shocks. Conversely, the steady improvement in food subsystem security underpinned Jilin's rising CCD. This underscores that enhancing the security of critical subsystems, particularly energy, is fundamental to achieving systemic coordination.

(3) The obstacles of the energy system have the characteristics of structural prominence, cross-field relevance of the system, and inter-provincial heterogeneity. Energy self-sufficiency and per capita energy productivity are usually common obstacles in the energy system. The issues facing Heilongjiang Province mainly focus on the efficiency of water resources utilization and the contradictions in the relationship between water, grain, and energy. After the policy shock, Liaoning showed the characteristics of damage to the energy system and weak food security. Jilin Province is facing the double constraints of energy supply and agricultural water efficiency. The change in these obstacles over time reveals that the shift in policy logic has shifted from a growth-oriented focus to an emphasis on environmental constraints, and then to building systematic resilience.

(4) Resilience functions as a critical mediating variable that regulates the security–coordination relationship. Highly resilient subsystems effectively buffer external shocks and facilitate cross-system coordination, whereas low resilience amplifies vulnerabilities and hinders recovery. The insufficient resilience of Liaoning Province's energy subsystem amplified the negative impacts of policy shocks. Jilin Province achieved steady growth in coordination levels by enhancing the resilience of its water–food system in a balanced manner. Consequently, enhancing regional capacities for response, recovery, and adaptation should be a central priority for future WEF system optimization.

6.2. Policy Implications

Drawing on the diagnostic findings of this study, we propose a targeted policy framework to advance the WEF system in Northeast China from moderate- to high-level coordination. The recommendations below, structured around the core issues of regional heterogeneity, system linkages, and resilience, are designed to inform sustainable governance in Northeast China and other resource-intensive regions facing similar challenges.

(1) Implement differentiated governance strategies based on regional heterogeneity. Research findings indicate significant differences in the development levels, dominant bottlenecks, and vulnerability structures of the WEF systems across the three provinces. This necessitates moving away from a one-size-fits-all policy approach toward differentiated and targeted governance. For regions like Heilongjiang Province, where agricultural water use pressures system stability, the priority is to enhance water-use efficiency. Governments can establish dedicated funds to promote smart irrigation and water–fertilizer integration technologies, substantially improving agricultural water conservation. Meanwhile, it should explore the establishment of water rights trading markets based on the concept that virtual water can incentivize agricultural water savings and redistribute these benefits through market mechanisms, thereby alleviating water resource pressures. Taking Liaoning Province as a representative case, grappling with structural energy vulnerability and fragile food security, policy must tackle a dual mission: advancing energy transition while bolstering food production. This requires that fiscal support for local renewable energy (wind, solar, biomass) be provided to boost self-sufficiency, and launching special initiatives for black soil conservation and high-standard farmland construction to secure the grain production base. In regions like Jilin Province, facing relatively balanced constraints, the focus should be on fostering technological synergy and spatial optimization. A proposed action is creating “green electricity–water conservation” demon-

stration zones, linking western renewable energy bases with central grain-producing areas through direct green power supply policies and integrated water–energy–fertilizer saving technologies.

(2) Build institutional mechanisms that foster a virtuous cycle between security and coordination. Given the bidirectional reinforcement between subsystem security and CCD revealed by this study, policy must actively foster this linkage. First and foremost, to incentivize holistic governance, integrate CCD assessments into local government performance evaluations, and add cross-system synergy modules to resource, energy, and food security accountability systems. Secondly, to enable proactive intervention, establish contingency plans for resilient resource allocation, triggered by CCD early-warning alerts. For instance, a sharp decline in a key subsystem’s security (e.g., Liaoning’s energy sector) would activate cross-departmental consultations and reallocation plans (e.g., adjusting grid dispatch or grain reserves) to prevent systemic coordination breakdown.

(3) Execute targeted interventions at key leverage points and their cross-system linkages. The obstacle degree model identifies high-impact indicators (e.g., C1-3 Energy Self-Sufficiency Rate, C2-1 Proportion of Water-Saving Irrigated Area). Policy should prioritize these points. Firstly, the government can take direct indicator-based actions: for the primary obstacle indicator C1-3, regional-level planning should establish integrated wind-solar-storage bases with supporting cross-provincial power consumption guarantee mechanisms; for the key obstacle indicator C2-1, it should mandate modern irrigation systems in high-standard farmland projects, supported by targeted subsidies. Secondly, cross-system transmission effects of obstacle factors must be addressed. Design integrated policies to tackle interconnected obstacles. A “water-grain” conservation policy could offer dual incentives for adopting water-saving tech (addressing A2, B6). Pilot “green electricity for irrigation” projects could break the chain of high pumping costs driven by low energy self-sufficiency (addressing C1-3’s impact on agriculture). Last and foremost, Northeast China should implement dynamic resilience management. Embed these key indicators (e.g., C1-3, C2-1) into a monitoring and early-warning system. Deviation from safety thresholds would automatically trigger cross-departmental consultations and pre-defined resource reallocation plans, sustaining the “security-coordination” cycle.

(4) Integrate the principle of systemic resilience into long-term planning and investment. As a critical mediator between security and coordination, enhancing resilience is fundamental for sustainable system operation. The first step, enhancing resilience, should become a fundamental strategy for ensuring the long-term stable operation of systems. This requires comprehensively integrating resilience indicators into the comprehensive evaluation system for infrastructure investment. When approving major water conservancy, energy, and agricultural projects, evaluations should extend beyond their immediate supply capacity to assess contributions toward enhancing the system’s long-term adaptability and resilience (e.g., storage, grid flexibility, soil moisture retention). Priority should be given to multifunctional, adjustable, and resilient infrastructure. The second step is for the state to propose establishing a regional WEF System Resilience Fund. This fund should target three key areas: First, supporting R&D and deployment of adaptive technologies addressing climate uncertainty, such as drought-resistant crops and smart agriculture models. Second, funding for building system recovery capacity, including developing rapid post-disaster restoration plans and establishing backup infrastructure networks. Third, enhancing society’s overall learning and adaptation capabilities, such as constructing integrated big data platforms and decision-making simulation systems to strengthen stakeholders’ risk awareness and collaborative governance capabilities. Embedding resilience in this manner is essential for maintaining the virtuous cycle of security and coordination under increasing uncertainty.

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Abbreviations

The following abbreviations are used in this manuscript:

WEF	Water–Energy–Food
CCD	Coupling Coordination Degree

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